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Hybrid pneumatic-electromagnetic launcher - general concept, mathematical model and results of simulation

Abstract. *The electromagnetic launcher is a specific type of electromechanical converter. Electrical energy from the power supply, discharging in the pulse way, is used for acceleration a moveable element (bullet). The electromagnetic launchers are widely used in applications ranging from military applications and ending on the basic research on the physical properties of materials. This paper presents the results of research conducted in the Department of Mechatronics, which included an analysis of the mathematical model (field-circuit) of the hybrid electromagnetic launcher with pneumatic assist. The purpose of this article is to present the results of simulations.*

Streszczenie*. Wyrzutnia elektromagnetyczna to specyficzny rodzaj przetwornika elektromechanicznego. Energia elektryczna pozyskiwana ze źródła prądu stałego, rozładowywana w sposób impulsowy, jest wykorzystywana do procesu rozpędzania elementu ruchomego (pocisku). Wyrzutnie elektromagnetyczne mają szerokie zastosowania począwszy od zastosowań militarnych a kończąc na badaniach fizycznych własności materiałów. W artykule przedstawiono wyniki badań symulacyjnych, przeprowadzonych w Katedrze Mechatroniki Politechniki Śląskiej, dla hybrydowej wyrzutni elektromagnetycznej ze wspomaganiem pneumatycznym. (****Hybrydowa wyrzutnia pneumatyczno-elektromagnetyczna - ogólna koncepcja, model matematyczny oraz wyniki badań symulacyjnych****).*

Keywords: electromagnetic launcher, coilgun, railgun.
Słowa kluczowe: wyrzutnia elektromagnetyczna, wyrzutnia elektromagnetyczna o napędzie cewkowym oraz szynowym.

Introduction

The idea of electromagnetic acceleration is a concept that was introduced at the beginning of the twentieth century. The first device implementing the construction electromagnetic acceleration was in 1920. This construction was named “the electric cannon” [2]. Actually there are also in use the following terms: electromagnetic launcher or electromagnetic gun. The rise in the intensity of research on electromagnetic accelerators was observed during the period of the Second World War when many laboratories experiments were carried out in various German research centers oriented at military applications. At that time main difficulty in developing this type of electromagnetic devices was lack of appropriate sources of energy. Intensive development of pulse power supplies, capacitors and supercapacitors in the end of 20th century caused again significant interest in electromagnetic launcher theme. Nowadays many research centers all over the world work on problems related to design, construction, optimization and new applications of electromagnetic launchers.

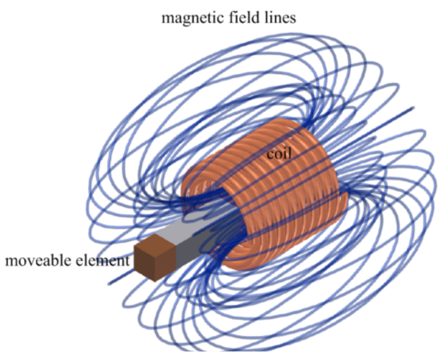

Fig.1. General concept of a coilgun

Let us remind that the electromagnetic launcher is a specific type of an electromechanical converter in which the electrical energy obtained from a DC source is used for rapid acceleration of a movable element (projectile). It is worth underlining that maximum velocity of the moveable element which can be obtained in electromagnetic launcher is very high (even tens of times greater than the speed of sound) what results from very sudden process of releasing large amounts of electrical energy which in very short time is converted in mechanical kinematic energy [2,9].

The electromagnetic launchers can be divided into two basic categories:

- coilgun in which the movable element made of a ferromagnetic material is placed inside a coil producing magnetic field [1],
- railgun in which a movable copper element is placed between two rails carrying current [7].

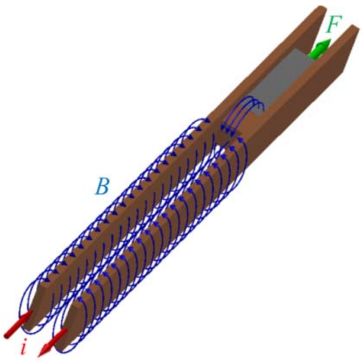

Fig.2. General concept of a railgun

There are wide variety of possible applications of electromagnetic launchers as non-conventional linear drives. Among them there are some very sophisticated proposals: electromagnetic guns for war ships (military purpose), launchers for satellites (cosmic space technology), high–pressure (for advanced physical research) or simulator of collisions between meteoroids and the surface of the Earth [1,3,4,5,6].

As regards pneumatic launcher, its concept is older than the concept of electromagnetic gun. Even a very popular air gun can be treated as simple example of a pneumatic launcher.

Main idea of this paper is to integrate and put together in one common construction: an electromagnetic launcher and a pneumatic launcher. This construction will be further termed a pneumatic-electromagnetic launcher. The authors present advantages of such a solution resulting from results of simulations. It is worth emphasizing that the prototype of a pneumatic-electromagnetic launcher was constructed and the elaborated mathematical model was experimentally verified [8].

The general concept of the hybrid launcher as a multidimensional control object

The hybrid pneumatic-electromagnetic launcher whose general concept is presented in Fig.3. consists of:

- pneumatic module (denoted further as a module P) whose task is to start motion of a moveable element and to give its introductory velocity,
- electromagnetic module equipped in a coil (denoted further as a module C) whose task is to continue acceleration process,
- electromagnetic module equipped in a rails (denoted further as a module R) whose task is to finalize acceleration process.

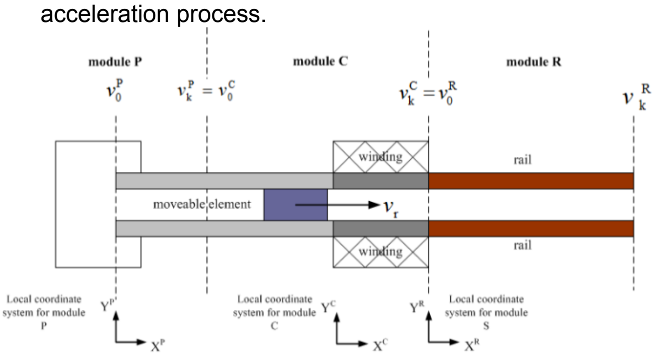

Fig.3. Conceptual design of the hybrid pneumatic-electromagnetic launcher, where: v_0^P – initial velocity of the moveable element in the module P, v_k^P – final velocity of the moveable element in the module P , v_0^C – initial velocity of the moveable element in the module C, v_k^C – final velocity of the moveable element in the module C, v_0^R – initial velocity of the moveable element in the module R, v_k^S – final velocity of the moveable element in the module P, v_r – velocity of the moveable element.

As can be seen in Fig. 4, there are 5 input (control) variables which can be adjusted (before firing) by the launcher's operator:

- P_0– initial value of the argon pressure in the pneumatic module ,
- U_{c0}^C – voltage initial value for capacitors battery supplying module C,
- U_{c0}^R – voltage initial value for capacitors battery supplying module R,

and additionally:

- $t_{on}(x^C)$ – moment of activating the module C,
- $t_{off}(x^C)$ – moment of deactivating the module C.

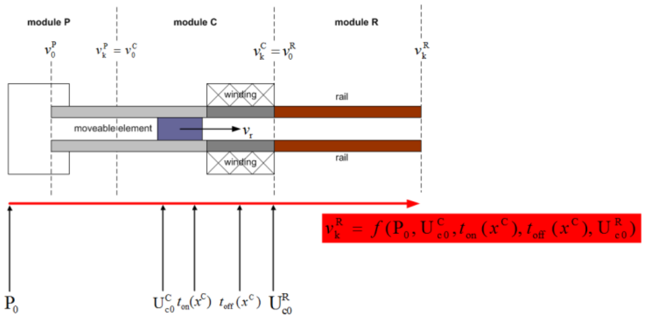

Fig.4. Control variables of the hybrid pneumatic-electromagnetic launcher

The elaborated mathematical (circuit-field) model which will be presented in chapter 4 takes into account the following electrical and mechanical variables important for analysing launcher behaviour from viewpoint of monitoring problems, as well as control problems:

- $i^R(t)$ – instantaneous value of the discharge current for module R,
- $i^C(t)$ – instantaneous value of the discharge current for module C,
- $v^R(t)$ – instantaneous value of velocity of the moveable element for module R,
- $v^C(t)$ – instantaneous value of velocity of the moveable element for module C,
- $x^R(t)$ – instantaneous value of displacement of the moveable element for module R,
- $x^C(t)$ – instantaneous value of displacement of the moveable element for module C,
- $a^R(t)$ – instantaneous value of acceleration of the moveable element for module R,
- $a^C(t)$ – instantaneous value of acceleration of the moveable element for module C,
- $F^R(x^R, i^R)$ – instantaneous value of force acting on moveable element in the module R,
- $F^C(x^C, i^C)$ – instantaneous value of force acting on moveable element in the module C.

Circuit-field mathematical model of the hybrid pneumatic-electromagnetic launcher

The structure of this mathematical model (in form of block diagram) is presented in Fig.5.

As can be noticed, the model consists of the 3 blocks (3 sets of differential equations with initial conditions) which are solved one by one. The all differential equations related to the 3 blocks were implemented in Matlab/Simulink program as one whole, what means that equalities linking output and input variables of individual blocks are treated as internal relationships.

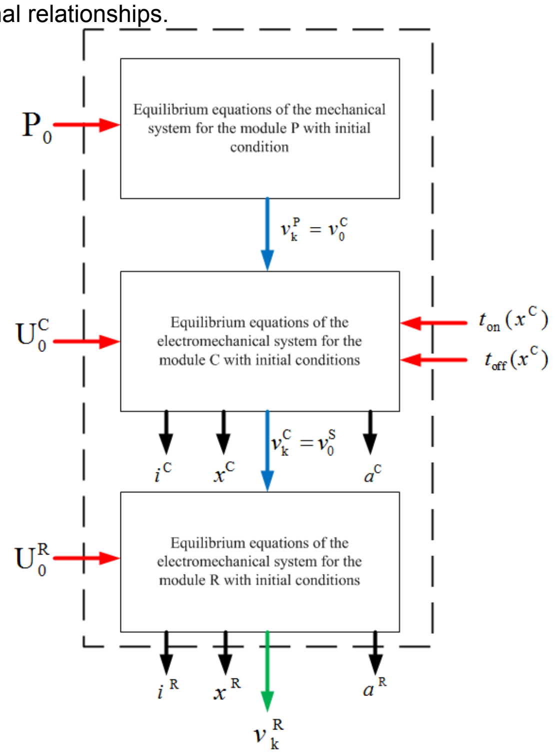

Fig.5. The block diagram of the integrated field-circuit model of the hybrid pneumatic-electromagnetic launcher

The integrated field-circuit model of the hybrid pneumatic-electromagnetic launcher consists of the 3 sets of differential equations corresponding to 3 blocks presented in Fig.5 :

- equilibrium equations for the moveable element connected with the module P:

(1)
$$\begin{cases} \dfrac{d^2x^P}{dt^2} = \dfrac{1}{m_r}\left(s_{rp}P_0\dfrac{V_0^{\kappa}}{(V_0+s_{rp}(x^P-l_r))^{\kappa}}-F_t^P\right) \\ v^P = \dfrac{dx^P}{dt} \\ a^P = \dfrac{d^2x^P}{dt^2} \end{cases}$$

initial condition:

(2) $$v^P\,(t = {}_{-}0) = v^P\,(t = {}_{+}\,0) = 0$$

where: m_r – mass of the moveable element, x^P - displacement of the moveable element for module P, s_{rp} – base area of the moveable element, P_0– initial value of the argon pressure in the pneumatic module, V_0 – volume of the reservoir with argon, l_r – length of the moveable element, κ – adiabat coefficient, v^P – velocity of the moveable element for the module P, a^P - acceleration of the moveable element for the module P.

- equilibrium equations for the moveable element connected with the module C:

(3)
$$\begin{cases} \dfrac{d^2u_c^C}{dt^2} = -\dfrac{1}{\dfrac{\partial\psi^C(x^C,i^C)}{\partial i^C}\cdot C^C}\left(u_c^C(t)+R^C(i^C)C^C\dfrac{du_c^C}{dt}+\dfrac{\partial\psi^C(x^C,i^C)}{\partial x^C}v^C\right) \\ \dfrac{d^2x^C}{dt^2} = \dfrac{1}{m_r}\left(F^C\,(x^C,i^C)-F_t^C\right) \\ v^C = \dfrac{dx^C}{dt} \\ a^C = \dfrac{d^2x^C}{dt^2} \end{cases}$$

initial conditions:

(4) $$u_c^C(t={}_{-}0)=u_c^C(t={}_{+}0)=U_{c0}^C,$$

(5) $$v^C\,(t={}_{-}0)=v^C\,(t={}_{+}0)=v_0^R,$$

where: u_c^C – voltage on the power supply for the module C, $\psi^C(x^C,i^C)$ – magnetic flux, $R^C(i^C)$ – total resistance of the module C, F_t^C – friction force,

- equilibrium equations for the moveable element connected with the module S:

(6)
$$\begin{cases} \dfrac{d^2u_c^R}{dt^2} = -\dfrac{1}{L^R(x^R)\cdot C^R}\left(u_c^R(t)+\left(R^R(x^R)+\dfrac{dL^R(x^R)}{dx^R}v^R\right)C^S\dfrac{du_c^R}{dt}\right) \\ \dfrac{d^2x^R}{dt^2} = \dfrac{1}{m_r}\left(F^R\,(x^R,i^R)-F_t^R\right) \\ v^R = \dfrac{dx^R}{dt} \\ a^R = \dfrac{d^2x^R}{dt^2} \end{cases}$$

initial conditions:

(7) $$u_c^R(t={}_{-}0)=u_c^R(t={}_{+}0)=U_{c0}^R,$$

(8) $$v^R\,(t={}_{-}0)=v^R\,(t={}_{+}0)=v_0^R.$$

where: u_c^R - voltage on the power supply for the module R, $L^R(x^R)$ – total inductance of the module R, $R^R(x^R)$ – total resistance of the module R, F_t^S – friction force.

Set of equations (3) includes the function of the electromagnetic force $F^C=f(x^C,i^C)$ acting upon the movement element in the module C. The value of this force as a function of displacement x^C and current i^C was determined with the help of finite element method. The two-dimensional function $F^C=f(x^C,i^C)$ is presented in Fig.6.

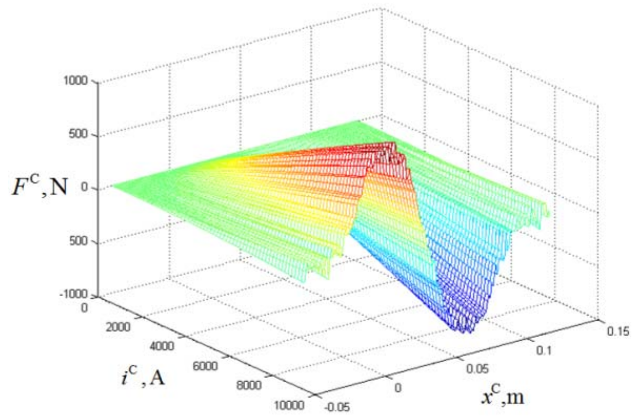

Fig.6. The force acting on the moveable element F^C as a function of displacement x^C and current i^C

The electrodynamic force $F^R=f(x^R,i^R)$acting upon the movement element in the module R, was calculated in similar way (with use of finite element method) and is presented in Fig.7.

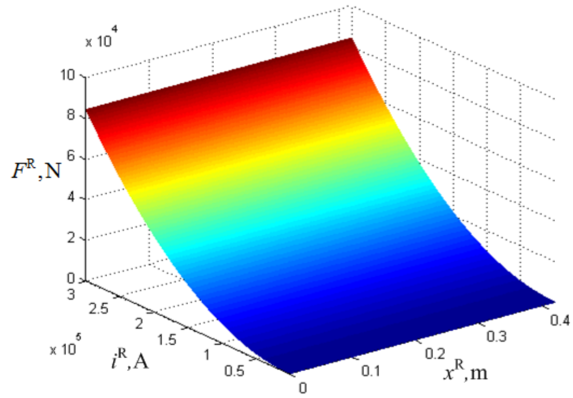

Fig.7. The force acting on the moveable element F^R as a function of displacement x^R and current i^R

The value of friction force was determined in experimental way. In the elaborated construction the movement element moves mainly along teflon barrel (module C) and teflon cradle (module R) having low value of friction coefficient. As a consequence, friction forces influence very slightly of movement element behaviour. Aerodynamic resistance in the module P was neglected because of special construction of pneumatic cylinder. The cylinder is equipped in deliberately-designed holes enabling compressed air in front of the moveable element to get out.

Simulation results

The program of simulation allowing to investigate influence of input (control) variables on process of acceleration of the movement element was elaborated.

The selected results of simulation oriented at time function of currents, displacements, velocities and accelerations for the module C and module R are shown in Fig.8.÷Fig.11 and Fig.12.÷Fig.15, respectively.

In the module R the greatest impact upon acceleration of the moveable element has the first “half-wave” of the current flowing in the rails. In the time of the first “half-wave” the moveable element achieves about 85% of the final (output) velocity.

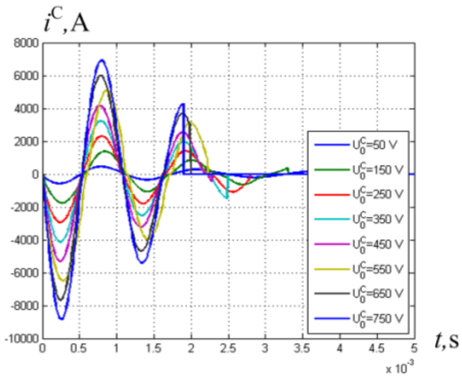

Fig.8. The time plots of the current i^{C} for $\mathrm{v}_0^{\mathrm{C}} = 10\ \frac{\mathrm{m}}{\mathrm{s}}$

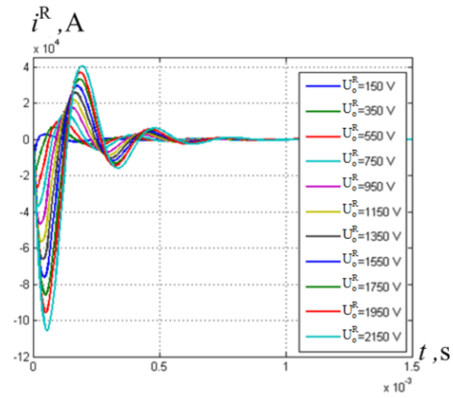

Fig.12. The time plots of the current i^{R} for $\mathrm{v}_0^{\mathrm{R}} = 50\ \frac{\mathrm{m}}{\mathrm{s}}$

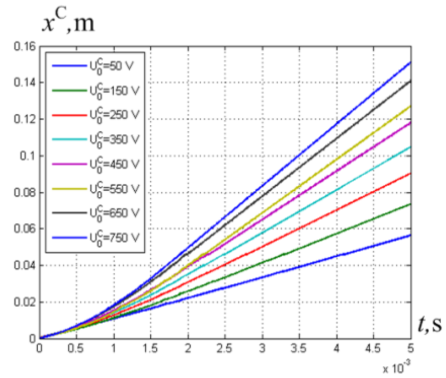

Fig.9. The time plots of the displacement x^{C} for $\mathrm{v}_0^{\mathrm{C}} = 10\ \frac{\mathrm{m}}{\mathrm{s}}$

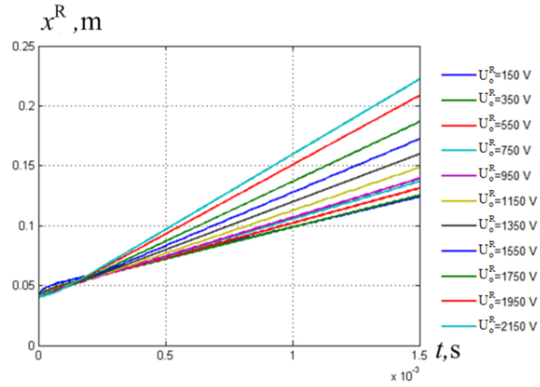

Fig.13. The time plots of the displacement x^{R} for $\mathrm{v}_0^{\mathrm{R}}= 50\ \frac{\mathrm{m}}{\mathrm{s}}$

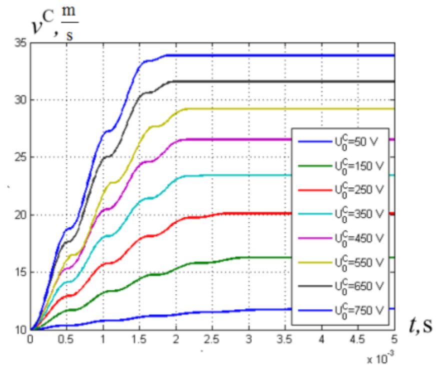

Fig.10. The time plots of the velocity v^{C} for $\mathrm{v}_0^{\mathrm{C}} = 10\ \frac{\mathrm{m}}{\mathrm{s}}$

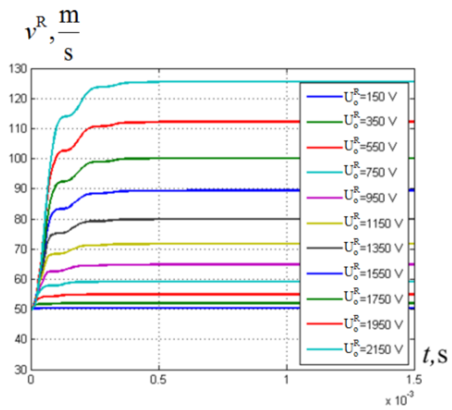

Fig.14. The time plots of the velocity v^{R} for $\mathrm{v}_0^{\mathrm{R}} = 50\ \frac{\mathrm{m}}{\mathrm{s}}$

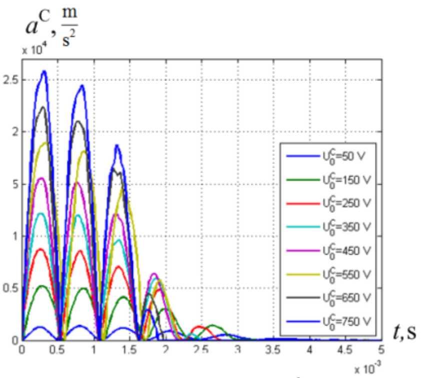

Fig.11. The time plots of the acceleration a^{C} for $\mathrm{v}_0^{\mathrm{C}} = 10\ \frac{\mathrm{m}}{\mathrm{s}}$

In the module C the greatest impact upon acceleration has initial velocity $\mathrm{v}_0^{\mathrm{C}}$, initial battery voltage $\mathrm{U}_{\mathrm{c}0}^{\mathrm{C}}$ and moments of the activating and deactivating module C. As may be seen, the optimum moment of activation should be determined in relation to the position of the moveable element along the coil.

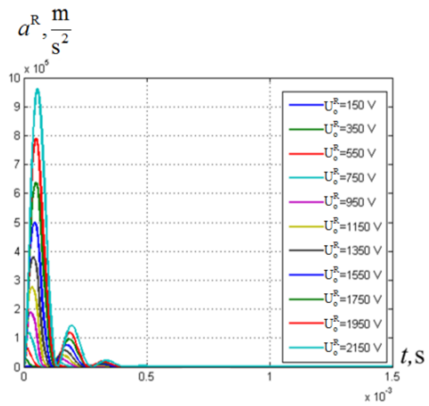

Fig.15. The time plots of the acceleration a^{R} for $\mathrm{v}_0^{\mathrm{R}}= 50\ \frac{\mathrm{m}}{\mathrm{s}}$

In the case in point the best moment of activation (t=t_{on}) corresponds to the position of the moveable element equal to zero ($x_0^{\mathrm{C}} = 0$).

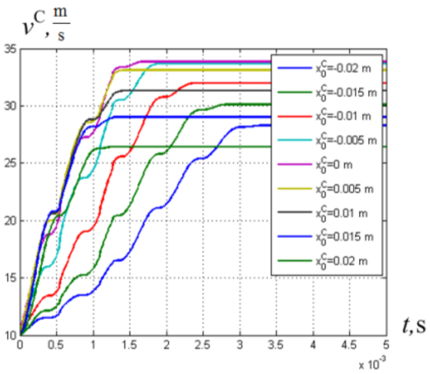

Fig.16. The time plots of the velocity of moveable element v^{C} in the module C for different moments of its activation, referred to the positions of the movable element along the coil x_0^C

Summary

Comparing the proposed hybrid 3-module pneumatic-electromagnetic launcher with the classical purely-electromagnetic single module, one can notice that the hybrid construction gives remarkably wider opportunity to influence acceleration process of the moveable element. It results from the fact that the number of input (control) values is increased to 5. It is also possible to interact with moveable element during its motion.

The elaborated mathematical (circuit-field) model and the results of simulation enable to determine the best strategy for acceleration and launching the moveable element.

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